

## PROCESS ANALYSIS BASED ON EXPERIMENTAL TESTS AND NUMERICAL MODELLING OF SINGLE POINT INCREMENTAL FORMING OF SHEET METAL: EFFECT OF THE PRINCIPAL PROCESS PARAMETERS

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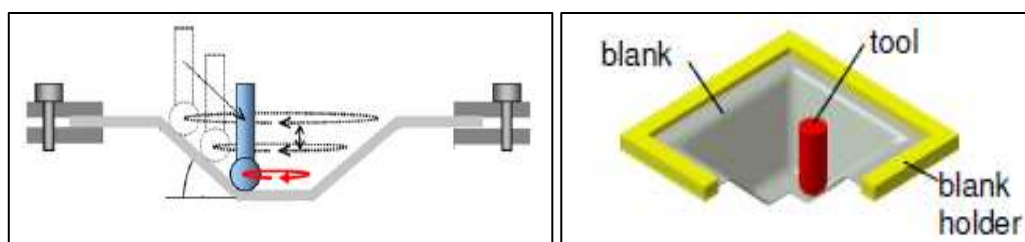
**Key words:** Single Point Incremental Forming (SPIF), CNC Programming, Experimental Investigation, Finite Element Modelling, Punch Force Evolutions.

**Abstract.** Incremental sheet forming (ISF) is a very promising technology to manufacture sheet metal products by the CNC controlled movement of a simple forming tool. It is considered as an innovative and flexible sheet metal forming technology for small batch production and prototyping, which does not require any dedicated die or punch to form a complex shape. Although incremental sheet forming is a slow process, the cost reduction linked to the fact that punches or dies are avoided, makes it a very suitable process for low series production, in comparison with the traditional stamping or drawing processes. This paper investigates the process of single point incremental forming of aluminum truncated cones and square pyramids geometries both experimentally and numerically. Concerning the numerical simulation, the finite element models are established to simulate the process by using a static implicit finite element code ABAQUS/Standard. In this article, the reported approaches were mainly focused on the influence of some crucial computational parameters. The influence of several parameters will be discussed: the initial sheet thickness and the workpiece geometry. The output of the simulation is given in terms of the punch forces evolution generated in this forming process and the final geometry. A comparison between the simulation results and the experimental data is made to assess the suitability of the numerical models. Experimental and numerical results obtained allow having a better knowledge of mechanical responses from different parts manufactured by SPIF with the aim to improve their accuracy. Predicted results show good agreement with experimental data for these geometries of the cones and pyramids. It is also concluded that the numerical simulation might be exploited for optimization of the incremental forming process of sheet metal.

### 1 INTRODUCTION

Single point incremental forming (SPIF) is an innovative process which allows to produce complex sheet components by CNC movement of a simple tool, with or without the combined use of simple dies [1]. Blank material is completely clamped by a simple frame and an

hemispherical punch is used as deforming tool (Figure 1). In this context, Single Point Incremental Forming may constitute a suitable industrial alternative, especially if one or few parts have to be produced, since no expensive dies are required. In the mean time, process mechanics is mainly characterised by stretching condition [2]: therefore a relevant sheet thinning occurs, which penalizes process suitability. More in detail, sheet thinning in the deformed zone may be approximated through the well known sine law, which relates the final thickness to the slope of the formed surface [3]. Actually some relevant deviations from this simple model are highlighted carrying out simple SPIF experiments.



**Figure 1:** Single point incremental forming SPIF

Many papers have been published on the incremental forming process of sheet metal, most of which are concerned with the experimental work [4-6]. In this context and since the 2005 review article, Ham and Jeswiet [7,8] performed an experimental investigation on the effects of process variables on formability of various aluminum alloys in a systematic way using two factorial designs of experiments. They used the maximum formable angle as the measure of formability. Process variables studied included feed rate, spindle rotation speed, step size and forming angle. It was reported that faster spindle rotation speed improves formability and step size has little effect on the maximum forming angle, whereas the material thickness, tool size and the interaction between material thickness and tool size have a considerable influence on maximum forming angle. Kopac and Kampus [9] presented in their work the process controlled by CNC milling machine-tool together with CAD/CAM Master Cam system and a smooth forming tool. With experimental testing and measurements the limits of forming without a full-size model were defined. By using a simple full-size model and the concept where the sheet metal can move vertically in the clamping device, better results and products were obtained. An evaluation of the maximum slope angle of simple geometries was carried out by Capece Minutolo et al. [10] by means of an incremental forming process of aluminum alloy sheets. In their applications, maximum slope angle of frustums of pyramid and cone has been evaluated. This evaluation has been performed by an experimental tests program, that has foreseen the carrying out of geometries for different slope angles, up to the observation of fractures. In the specific case, afterwards the mechanical characterization and the evaluation of the sheets formability, frustums of pyramid and cone, with different slope angles, have been carried out, up to the appearance of fractures in the sheet. Numerical simulation of incremental forming of sheet metal has been also carried out in some papers [11,12], in which however the tool path is relatively simple. Effect of tool path on the deformation behavior has not been discussed. Since there is no article to which can be referred for the practical use of the numerical simulation for this process, the authors think that it is of great worth to check its applicability from the view point of making the production process more efficient. Very recently some researchers have focused their attention on modelling and numerical simulation

in incremental forming. Hirt et al. [13] presented in their work two major process limits, namely the limitation on the maximum achievable wall angle, and the occurrence of geometric deviations. They proposed some forming strategies and process modelling for CNC incremental sheet forming to overcome these process limits, including the processing of tailor rolled blanks. Additionally, finite element modelling of the process is presented and discussed with respect to the prediction of the forming limits of ISF. In 2004, Bambach et al. [14] developed a finite element modelling of the ISF process. In particular, the outcome of different multistage strategies is modelled and compared to collated experimental results regarding aspects such as sheet thickness and the onset of wrinkling. Moreover, the feasibility of modelling the geometry of a part is investigated as this is of major importance with respect to optimizing the geometric accuracy. Experimental validation is achieved by optical deformation measurement that gives the local displacements and strains of the sheet during forming as benchmark quantities for the simulation. The numerical simulation may provide technical support to the designers only if the simulation time is comparable with the trial and error tests. With this aim, both experimental tests and three-dimensional FE model of single point incremental forming (SPIF), derived by the application of an explicit approach, have been developed by Ambrogio et al. [15] and a suitable application for the process design has been defined in their applications. Single point incremental forming (SPIF) suffers from process window limitations which are strongly determined by the maximum achievable forming angle [16]. In this subject, an experimentally explored multi-step tool paths strategy is reported and the resulting part geometries compared to simulation output. Sheet thicknesses and strains achieved with these multi-step tool paths were verified and contributed to better understanding of the material relocation mechanism underlying the enlarged process window. In the present research, deformation behaviour of sheet metal in single point incremental forming process (SPIF) is numerically simulated using a static implicit finite element code ABAQUS/Standard. Furthermore, several incremental forming tests were carried out on Al 3003-O Aluminum Alloy blanks utilizing a properly designed fixture mounted on a 3-axis controlled CNC milling machine equipped with a special tool. The objective of this study is to investigate the effects of two commonly varied forming process parameters on the force required to form the sheet metal. These are the initial sheet thickness and the workpiece geometry. A useful control of the process by determining and monitoring the forces between the punch and the sheet is aimed. The effect of the initial thickness variation on the evolution of the efforts provided by tool is studied in addition to the influence of the final workpiece geometry on the thickness distribution of final product is also considered.

## **2 EXPERIMENTAL PLATFORM**

The research activity was carried out through the two following phases: first of all a set of experiments [17], characterized by different geometrical conditions, were carried out using a 3-axis CNC vertical milling machine (Figure 2) as a platform to develop the ISF process. The forming tool consists in a cylindrical rotating punch with 10 mm diameter and hemispherical end shape which it was used simply as a tool (one-point incremental forming). The tool path was specified on the CNC milling machine through a part program: for each test a subroutine has been developed to describe the tool trajectory from CAM procedure depending on the testing conditions. Such trajectory includes both the movement in the horizontal plane (i.e. the x-y table of the milling machine) and the tool depth at each loop along the Z-axis. The blank,

which had square shape and dimensions equal to 200 mm×200 mm, was clamped using a properly designed framework; in this way the punch determines the extension of the blank which undergoes plastic deformation due to the punch movement.



**Figure 2:** The experimental equipment for SPIF experiments (three-axis milling machine tool - SPIF tooling system) [17]

To analyse the punch load, the force measuring set-up is shown in figure 2. It consists of a table type force sensor which was mounted between a steel fixture and the milling machine work-surface. This was a Kistler 9265B six-component force dynamometer and connected to it was a complementary Kistler 5017A 8-channel charge amplifier. The measuring system also includes charge amplifiers, data acquisition cards and a PC. The sampling rate in force measurement was 50 Hz.

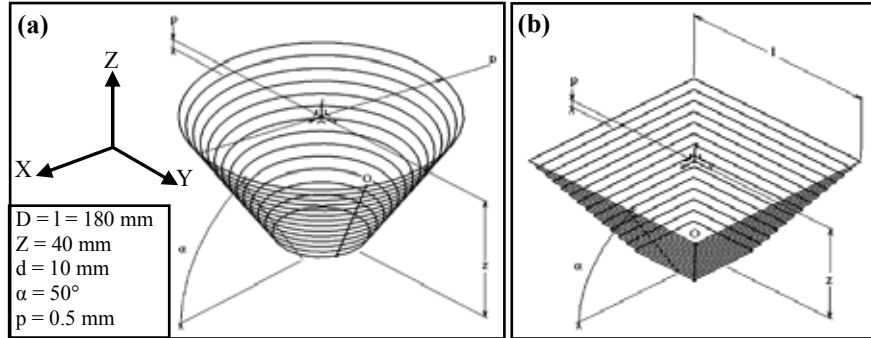
### 3 NUMERICAL MODELLING OF SINGLE POINT INCREMENTAL FORMING

In this study we consider the single point incremental forming operations (SPIF). It is a progressive sheet metal forming operation characterised by large displacements and strains, and located deformations. The punch is a simple smooth ended tool with a diameter far smaller than the dimension of the part being made. Proceeding in an incremental way, the tool is moved along contours which follow the shape of the final geometry as described by CAD and CAM of CATIA software. It is very difficult in general to predict the forming loads applied by the tools and the thickness strain distribution of the final state of a deformation after the accumulation of numerous incremental deformation passes. Recently, finite element method (FEM) has facilitated the calculation of the punch forces during the whole deformation process and the thickness strain. In this investigation, elasto-plastic analysis of SPIF process by finite element method (FEM) was performed using a finite element code ABAQUS<sup>®</sup> software capable of handling large deformation. Finite element models are established to simulate aluminum truncated cones and pyramids.

#### 3.1 The parts geometry of the applications

Reported simulations are mainly based on the production of simple workpiece geometry, a right truncated cone at 40 mm depth with circular base having the initial diameter of  $D = 180$  mm. The second model shape to undertake the numerical study represents a truncated pyramid at 40 mm depth starting from the square base side length of  $l = 180$  mm. These geometries for both the frustums of cone and pyramid are carried out with different

thicknesses and slope angles beginning from a square sheet with a side of 200 mm. The tool paths, whose examples are reported in figure 3, are characterized, for the frustums of cone, by a sequence of circular coils, the first of which presents  $D = 180$  mm, while the feed along an edge has a step size  $p = 0.5$  mm; for the frustums of pyramid, a sequence of square coils generates the tool path, the first of which presents  $l = 180$  mm, and the feed along a  $Z$  direction has a step size  $p = 0.5$  mm. For both of them, the maximum drawing depth is  $z = 40$  mm.

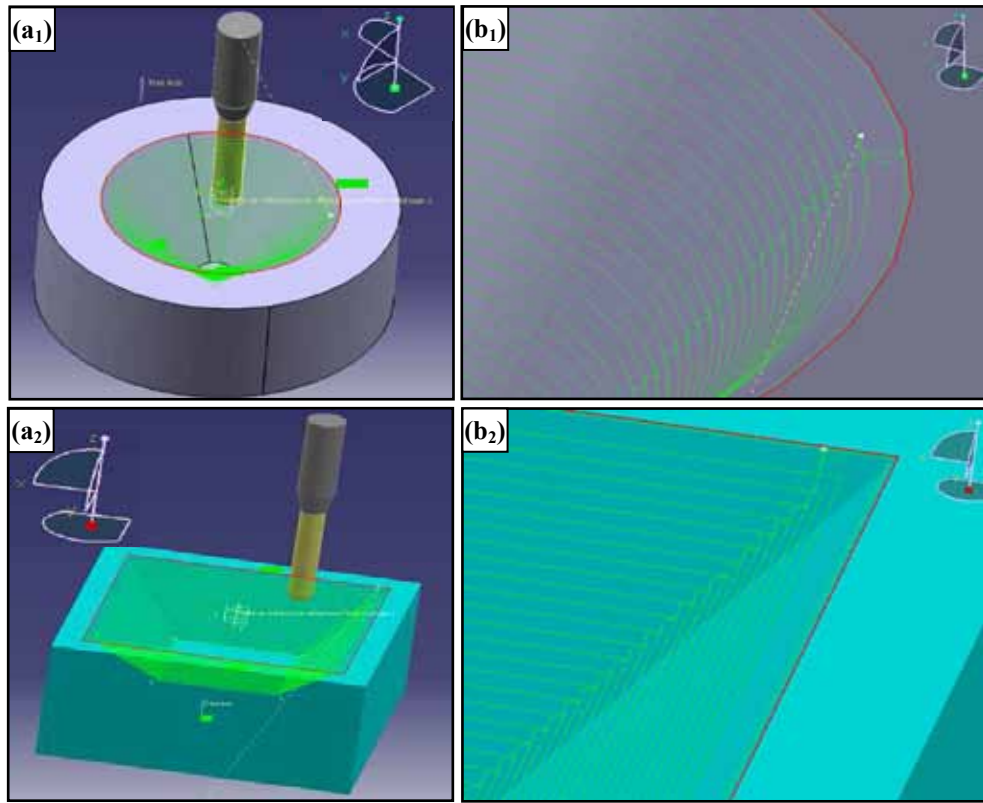


**Figure 3:** Geometries and dimensions carried out for some parts formed (a) Representative conical frustums with tool path and (b) Representative frustums square pyramid with tool path

The standard process parameters applied are 0.5 mm vertical step size, 10 mm tool diameter,  $50^\circ$  wall angle and the standard material used is 1.2 mm thick Al 3003-O [17]. Unless the parameter is being varied, these will be the constant values used.

### 3.2 Contour tool path generation using CATIA software

The determination of the trajectory defining the tool path becomes increasingly difficult depending strongly on the complexity of the final geometry of parts and the minimization of the incremental step size. In fact, the implementation of the trajectory in numerical model remains very difficult if a traditional methods based on manual calculation will be considered. Within the framework, we have to generate the trajectory describing the desired geometries characterizing the truncated cones and pyramids. Therefore in the present study, the parts were modelled in a commercial 3D CAD-CAM software CATIA V5R17, and the trajectories to control the tool motion in order to form the desired shapes were automatically generated with the CAM module. This software generates the tool path after defining all the parameters that characterize the working operation such as the tool dimensions, the step depth, etc... The path generation is automatic: the software evaluates and identifies the best tool path for the operation we want to do. Finally the 3D CAD/CAM uses a specific postprocessor to convert the trajectory of the tool so obtained into a numerical file. Figure 4a<sub>1</sub> shows the trajectory, described by the tool during the forming of frustum of cone. In the analysis, the tool path is of type discontinuous represented by a series of contours generated along the  $Z$ -axis of the cone. A detailed view on the discontinuity zone is displayed in figure 4b<sub>1</sub>. The geometrical shape of a pyramidal model and the corresponding discontinuous tool path are reported in figure 4a<sub>2</sub>. In the same manner as the first geometry of the conical model, a zooming view on the discontinuity zone of the trajectory is presented by figure 4b<sub>2</sub>. It is characterized by square tool paths with constant step depth forming a pocket. In the case, the forming tool moves from the top to the bottom of the pocket, in which it follows a series of consecutive  $Z$  constant



**Figure 4:** (a<sub>1</sub>) Discontinuous trajectory for conical model; (b<sub>1</sub>) A detailed view on the discontinuity zone; (a<sub>2</sub>) A tool path for pyramidal geometry: discontinuous trajectory and (b<sub>2</sub>) A detailed view on the discontinuity zone

contours with fixed step depth  $\Delta z$  constant during all the tool path. The steps shown are in sequential order and they are for incremental, unidirectional steps.

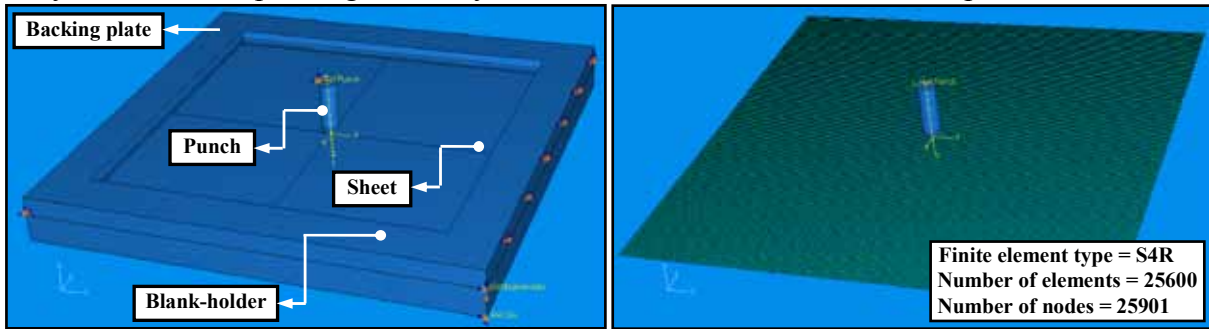
### 3.3 Description of the numerical model

As sheet metal forming involves large material rotation as well as strain, suitable algorithm should be employed in the FEA. In this investigation, a three-dimensional, elasto-plastic FE model is set up for the simulation of the SPIF process. Therefore, static simulations were conducted in this work by using the implicit FE package Abaqus/Standard like calculation algorithm capable of handling large deformation. Figure 5a reports the developed numerical model for the process in the initial position of tools. It shows the undeformed sheet modelled in this context. Modelling the interaction between the tool and the sheet is one of the most important considerations necessary to simulate the incremental forming process correctly. The punch, the blank-holder and the backing plate are modelled by adopting the assumption of an analytical rigid body hypothesis, while the sheet material is considered as elastic-plastic object. Since in the experiments the sheet was flooded with lubricant, the contact at the interface between sheet and tools follows Coulomb's friction law:

$$\tau_f = \mu \sigma_n \quad (1)$$



where  $\tau_f$  is friction shear stress,  $\sigma_n$  is normal stress at interface and  $\mu$  is the friction coefficient. Friction conditions between the forming tool and the sheet metal part have been accounted by considering sliding friction with a small relatively friction coefficient equal to  $\mu_p = 0.09$ . On the other hand, the value of the friction coefficient at the contact interfaces of blank-holder, sheet and designed backing plate is chosen to be equal to  $\mu_b = 0.15$ . Concerning the processing conditions including a punch displacement, the tool is considered as a rigid body and the corresponding boundary conditions are related to the defined path.



**Figure 5:** (a) Three-dimensional numerical simulation of single point incremental forming of sheet metal and (b) The finite element meshing configuration of the initial blank

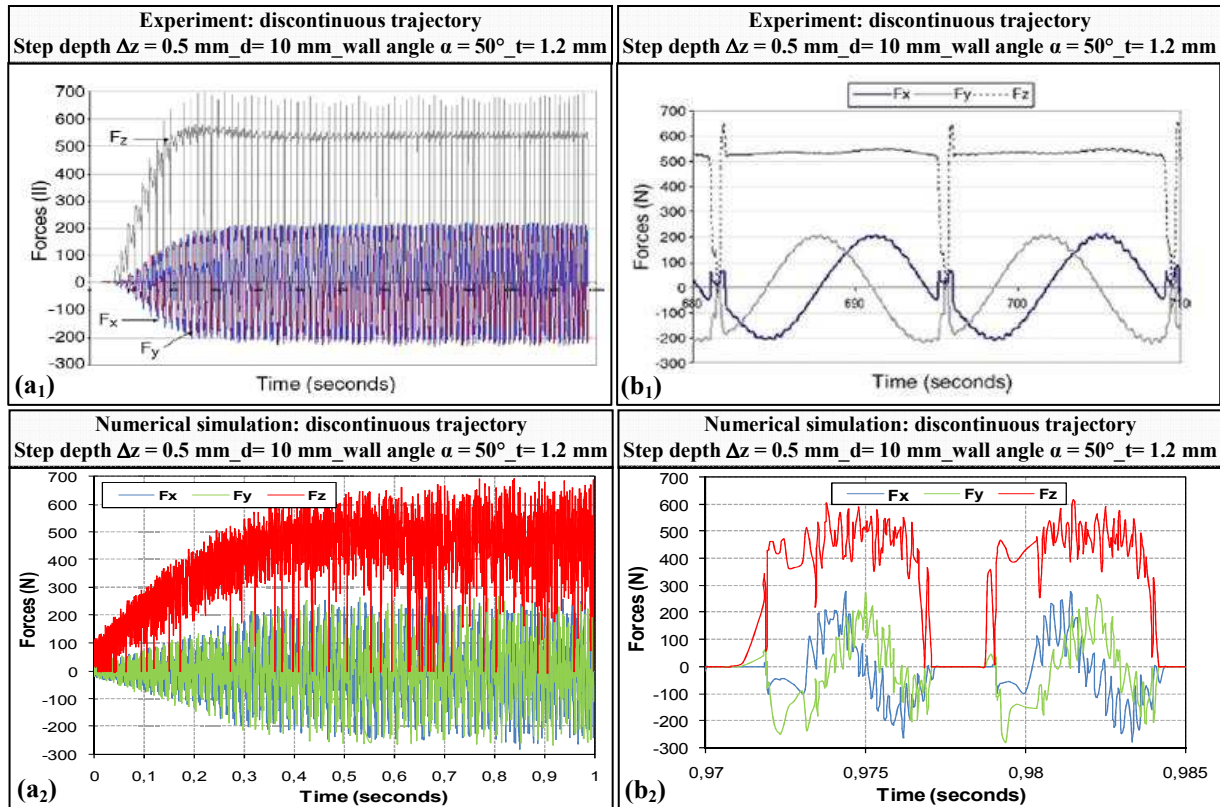
Due to the 3D tool path movement, a fully three-dimensional spatial analysis has been realized. The finite element meshing configuration of the initial blank is shown in figure 5b. As a consequence, quadrilateral shell elements with 4 nodes and 6 degrees of freedom per node (S4R) and five Gaussian reduced integration points through the thickness direction were used. This is suitable for nonlinear material models and widely used in the forming problems of large deformation and large rotation. Al 3003-O sheets with a size of 200 mm×200 mm have been considered for different thicknesses. In the FE model, the global size of elements is 1.25 mm×1.25 mm and the blank was initially meshed with 25600 finite shell elements and 25901 nodes. In this way, for each node, both displacements and rotations (i.e. 6 degrees of freedom for each node) are taken into account. Furthermore, the element is subjected to both tractions and moments at each step of the deformation path. All simulations were performed on Windows XP PC Core 2 Quad with 2.5GHz processor and a read/write memory performance of 2096 Megabytes. The CPU time required to simulate the single point incremental forming process of truncated cone or square pyramid mentioned previously takes on average 5 days.

#### 4 RESULTS AND DISCUSSION

This section provides information about the results obtained in the frame of the present work, with regards to the influence of different process parameters on the characteristics of the parts produced by incremental sheet forming and the comparison between the results predicted by the numerical model and the ones obtained experimentally. The objectives of these studies are to identify and analyze the effects of the principal geometrical parameters related to the initial sheet thickness, the wall angle and the part shape on the characterization of the process.

#### 4.1 Force components acting on traveling punch during the incremental forming process

The graphs of figure 6 summarize the time plot of punch forces attained during the single point incremental forming process of the Al 3003-O Aluminum Alloy blanks. The evaluations of the magnitude of the loads provided by the punch in incremental CNC sheet metal forming process were investigated by applying two approaches: experimental analysis and numerical modelling on forces determination for improving knowledge of single point incremental forming. Both figures 6a<sub>1</sub> and 6a<sub>2</sub> represent the evolution of the three force components measured and predicted by experimental and numerical approaches respectively throughout the incremental forming process by producing a cone with standard process parameters by using a 10 mm diameter tool. The tool path used in this part of analysis follows a discontinuous trajectory. The initial thickness of the sheet metal before its working is fixed at a value equal to 1.2 mm. As it can be concluded from these graphs, a typical force curves start at zero once forming is initiated. As the tool pushes deeper into the metal, the force quickly increases until a depth is reached where the forces tend to remain approximately constant.



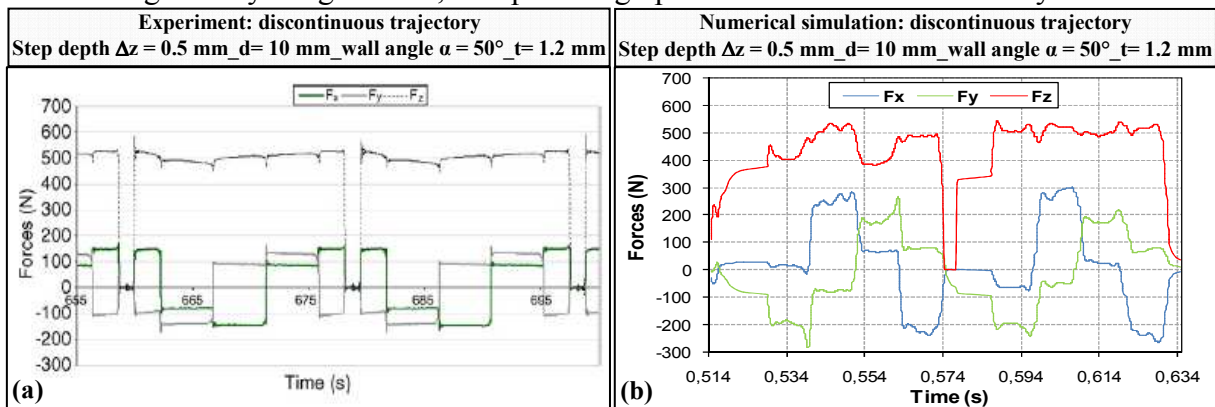
**Figure 6:** Experimental and numerical results for punch forces during the SPIF process by producing a cone with standard process parameters (a<sub>i</sub>) Evolution of three forces components ( $F_x$ ,  $F_y$  and  $F_z$ ) exerted on the sheet metal (b<sub>i</sub>) A detailed views of the forces measured experimentally and predicted by numerical simulation

This occurs for a number of reasons. Firstly, the tool does not have a contact area that is fully evolved until a number of contours have been made, and secondly, any effect induced by starting near the edge of the backing plate must be overcome. Comparing the force components measured in the experiment shown by figure 6a<sub>1</sub> and the force diagram calculated



by using FEA described in figure 6a<sub>2</sub>, it can be said that the force patterns in the X and Y directions are not equal. This is due to sheet anisotropy and non-symmetric deformation mode. With an aim of validating the developed numerical model, we chose to make a localized enlargement of the preceding figures (Figures 6a<sub>1</sub> and 6a<sub>2</sub>). This was meant to establish a more detailed comparison of the results determined by means of the two experimental and numerical approaches. Detailed views of the measured and simulated force components for two contours are demonstrated by figures 6b<sub>1</sub> and 6b<sub>2</sub>. It can be observed from these two results that after completion of one contour, the  $F_z$  component first drops to zero when the tool finishes a contour radius and it moves to the next one, before reaching its peak value at the step down. It finally stabilizes when the tool moves along the contour.  $F_x$  and  $F_y$  forces change between their minimum and maximum values in a sinusoidal way according to the tool position relative to the dynamometer axis within one contour. A comparison of the numerical efforts of various components illustrated in figure 6b<sub>2</sub> shows a fairly good agreement with collated experimental data (Figure 6b<sub>1</sub>). In fact, it can be noted a resemblance on the shape levels of curves into various representations. Except that we expect a minimal error of approximately 8% between the experimental amplitudes and those which are obtained from numerical calculations.

The square pyramid shaped box was formed on CNC milling machine, and it has been modelled by means of FEA. The force components were measured in X, Y and Z directions. Figures 7a and 7b show a detailed view of the experimental measures and the numerical prediction of three forces components ( $F_x$ ,  $F_y$  and  $F_z$ ) for two contours of the pyramid tool path. Unlike the forces in figure 6,  $F_x$  and  $F_y$  forces are approximately constant with changing sign depending on the tool position relative to the dynamometer. When the tool travels along the x-axis of the dynamometer, the  $F_x$  force reaches its maximum value, while the  $F_y$  force is at its maximum when the feed direction corresponds to the y-axis of the dynamometer. When the  $F_x/F_y$  force is at the maximum value, which corresponds to friction as well as to the limited forming action in the feed direction, the corresponding  $F_y/F_x$  force maintains an intermediate level. As it can be seen from the comparison of figures 7a and 7b, the force values are generally in agreement, except for high peak values in numerical study.



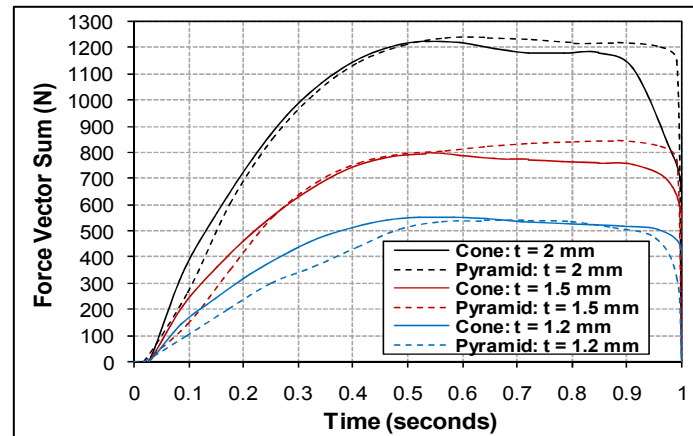
**Figure 7:** A detailed views of the forces  $F_x$ ,  $F_y$  and  $F_z$  for two contours of the pyramid tool path (a) Experimental investigation (b) Numerical prediction

Note that the time in figures 7a and 7b is not in scale, i.e. the comparison can be made considering the patterns of load curves. Generally these peaks occur in the corners of the

pyramid when the tool is making the vertical step downwards, as the tools' moving direction changes rapidly. Moreover, we find the points of discontinuity of the trajectory. The latter correspond to the zero values of the efforts and the resumption of a new cycle when a new incrementing is controlled by the tool.

#### 4.2 Influence of sheet thickness: force trend at the variation of initial sheet thickness

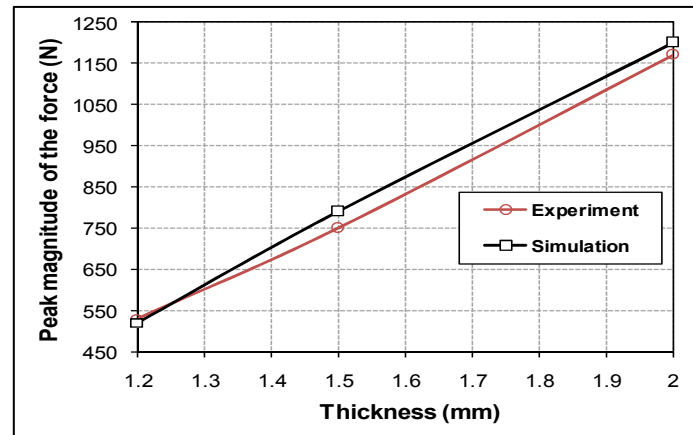
In order to make a comparison between the results obtained for conical and pyramidal geometry, we chose to represent all force vector sum curves in the same figure. Examples of the Abaqus predicted total forces acting on the traveling tool during forming operation are presented in figure 8 for cones and pyramids parts formed by using 1.2, 1.5 and 2 mm thick. From figure 8, it can be seen that the resultant forces for cones and pyramids evolve according to identical trends. The force vector sums for pyramids are of the same order of magnitudes as for cones for identical process parameters, although the individual  $F_x$ ,  $F_y$  and  $F_z$  force components show different patterns. First of all, the instantaneous simulated force value depends on the sheet thickness as shown in figure 8. Besides, a strong correlation exists between the forming load and the thickness: to put it in a more detailed way, the increase in the above-mentioned geometrical parameter leads to the increase of the numerically predicted load as well.



**Figure 8:** Simulated force curves for cones and pyramids parts formed using 1.2, 1.5 and 2 mm thick Al 3103-O: a comparison between the two parts geometry for discontinuous tool path

Figure 9 shows the results obtained in the force measurements performed in the way described previously, in comparison with the values of the magnitude of force required to form a given part predicted by the FEM process model. As the sheet thickness increases, it is apparent that this magnitude also rises. That is, the magnitude of force is directly proportional to the initial sheet thickness and fits well with the linear trends shown in the figure. As it can be noticed, experimental values are slightly lower than predictions, but results are very good, showing a discrepancy between the experimental results and the predictions of the model. The results obtained by two approaches make it possible to give the relative variation of the force amplitude compared to the experiment and expressed by:  $\Delta F(\%) = \left[ (F_{Exp} - F_{Num}) / F_{Exp} \right] \times 100$ . They are 2% and 3%, respectively for the smallest and greatest values of sheet thickness (1.2 mm and 2 mm). Consequently, the peak load evolution curve determined by the numerical

approach is thus in good agreement with the experimental one.



**Figure 9:** Influence of initial sheet thickness on the peak magnitude of the forming loads acting on the punch

## 5 CONCLUSIONS

This paper investigates the process of single point incremental forming of truncated cones and pyramids formed of an aluminum alloy sheet Al 3003-O both experimentally and numerically. In the first part of this paper, a deeper assessment of the process was developed following a set of numerical simulations and experimental tests in order to find the influence of some relevant process parameters, on the estimation and the repartition of the forming force components and to make a comparison between them. The obtained experimental and numerical results are found to be in agreement for the two models: conical and pyramidal geometries. In the second part of the work, a campaign of numerical tests has been carried out in a parametric form by varying systematically at each test the initial value of the sheet thickness during forming process. In this investigation, three FE simulations of the considered process were performed for the conical and pyramidal models, each having varied the material thickness. In particular, this study examines the effect of the considered geometrical parameter on the evolution of the resultant forming forces acting on the traveling tool. The results of the tests were analyzed quantitatively, and some observations were made as follows below:

- The forming force tends to increase with the sheet thickness, and this cannot be a negligible aspect.
- For a better comparison between the two conical and pyramidal shapes we chose to represent in the same figure the evolution of the corresponding resultant force curves parameterized in sheet thickness. According to the obtained results, it could be noted that the different efforts evolve in the same way. In fact, when the sheet thickness is increased, the forces will increase accordingly.

## REFERENCES

- [1] Bambach, M., Hirt, G. and Junk, S. Modelling and experimental evaluation of the incremental CNC sheet metal forming process. *In Proceedings of the seventh International Conference on Computational Plasticity ITCP* (2003).
- [2] Ambrogio, G., Filice, L., Fratini, L. and Micari, F. Some relevant correlations between

- process parameters and process performance in incremental forming of metal sheets. *In Proceedings of the sixth International Conference on Material Forming ESAFORM* (2003) 175-178.
- [3] Kitazawa, K., and Nakajima, A. Cylindrical incremental drawing of sheet metals by CNC incremental forming process. *In Proceedings of the sixth International Conference on Computational Plasticity ICTP* (1999) 1495-1500.
  - [4] Mori, K., Yamamoto, M. and Osakada, K. Determination of hammering sequence in incremental sheet metal forming using a genetic algorithm. *J. Mater. Process. Technol* (1996) **60**:463-468.
  - [5] Dai, K., Wang, Z.R. and Fang, Y. CNC incremental sheet forming of an axially symmetric specimen and the locus of optimization. *J. Mater. Process. Technol* (2000) **102**:164-167.
  - [6] Kim, Y.H. and Park, J.J. Effect of process parameters on formability in incremental forming of sheet metal. *J. Mater. Process. Technol* (2002) **130/131**:42-46.
  - [7] Ham, M. and Jeswiet, J. Single point incremental forming and the forming criteria for AA3003. *Annals of the CIRP - Manufacturing Technology* (2006) **55(1)**:241-244.
  - [8] Ham, M. and Jeswiet, J. Single point incremental forming limits using a box-behnken design of experiment. *Key. Eng. Mater* (2007) **344**:629-636.
  - [9] Kopac, J. and Kampus, Z. Incremental sheet metal forming on CNC milling machine-tool. *J. Mater. Process. Technol* (2005) **162-163**:622-628.
  - [10] Capece Minutolo, F., Durante, M., Formisano, A. and Langella, A. Evaluation of the maximum slope angle of simple geometries carried out by incremental forming process. *J. Mater. Process. Technol* (2007) **194**:145-150.
  - [11] Iseki, H. An approximate deformation analysis and FEM analysis for the incremental bulging of sheet metal using a spherical roller. *J. Mater. Process. Technol* (2001) **111**:150-154.
  - [12] Shim, M.S. and Park, J.J. The formability of aluminum sheet in incremental forming. *J. Mater. Process. Technol* (2001) **113**:654-658.
  - [13] Hirt, G., Ames, J., Bambach, M. and Kopp, R. Forming strategies and process modeling for CNC incremental sheet forming. *Annals of the CIRP - Manufacturing Technology* (2004) **53(1)**:203-206.
  - [14] Bambach, M., Hirt, G. and Ames, J. Modeling of optimization strategies in the incremental CNC sheet metal forming process. *In Proceedings of the eighth International Conference on Numerical Methods in Industrial Forming Processes NUMIFORM* (2004) **712**:1969-1974.
  - [15] Ambrogio, G., Filice, L., Gagliardi, F. and Micari, F. Three-dimensional FE simulation of single point incremental forming: experimental evidences and process design improving. *In Proceedings of the eighth International Conference on Computational Plasticity COMPLAS* (2005) Barcelona, Spain.
  - [16] Duflou, J.R., Verbert, J., Belkassam, B., Gu, J., Sol, H., Henrard, C. and Habraken, A.M. Process window enhancement for single point incremental forming through multi-step toolpaths. *Annals of the CIRP - Manufacturing Technology* (2008) **57(1)**:253-256.
  - [17] Duflou, J.R., Tunçkol, Y., Szekeres, A. and Vanherck, P. Experimental study on force measurements for single point incremental forming. *J. Mater. Process. Technol* (2007) **189**:65-72.